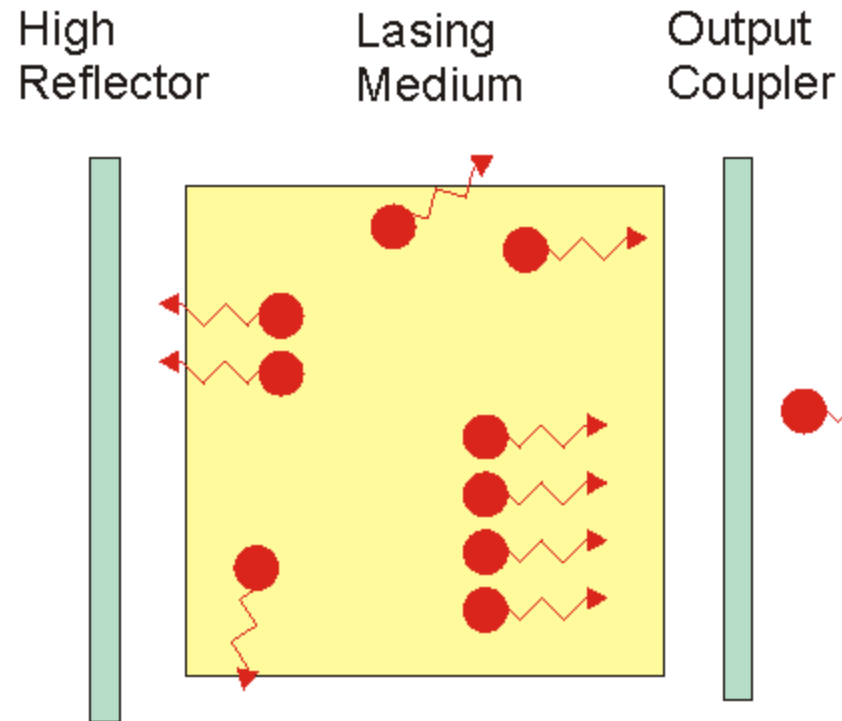


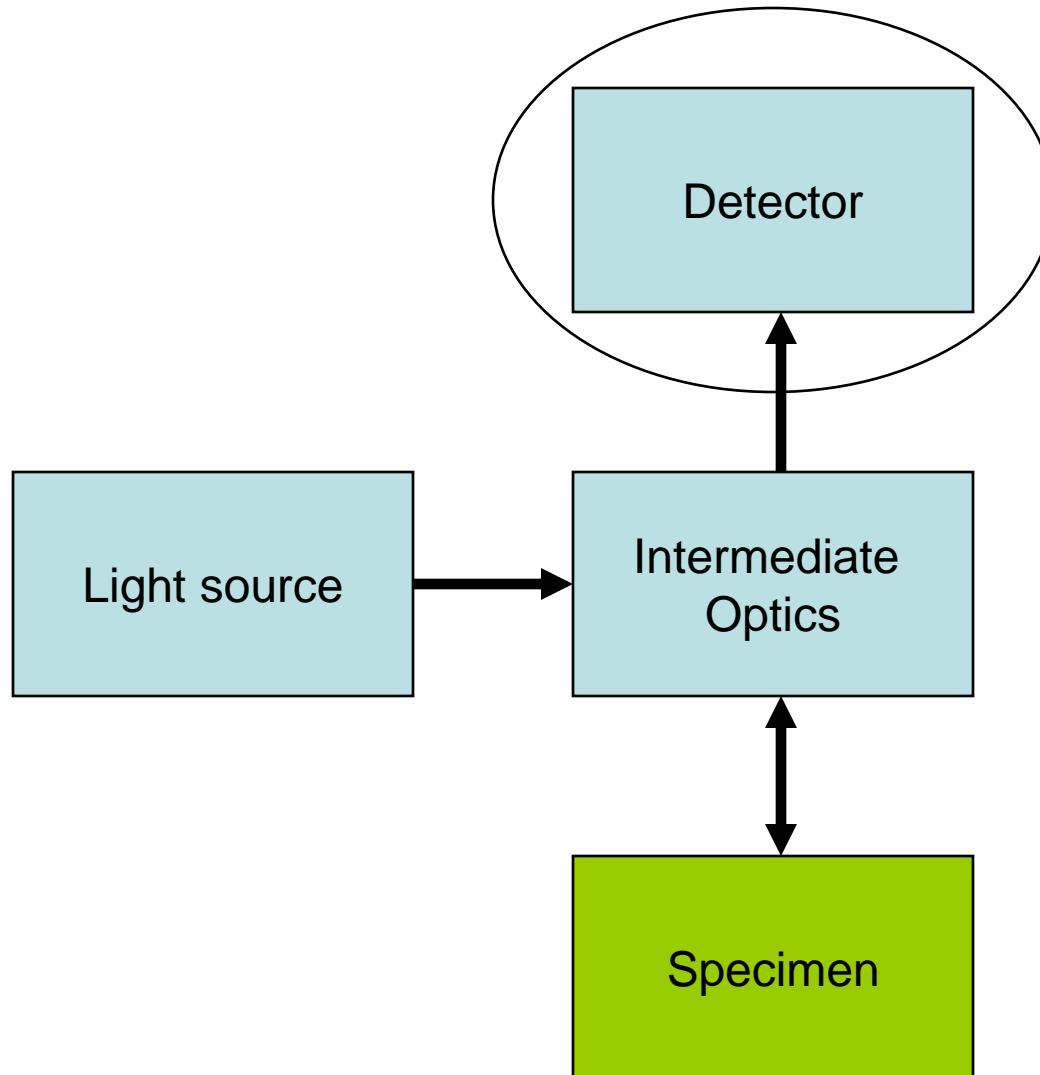
Optoelectronics III



What have we learned last lecture:

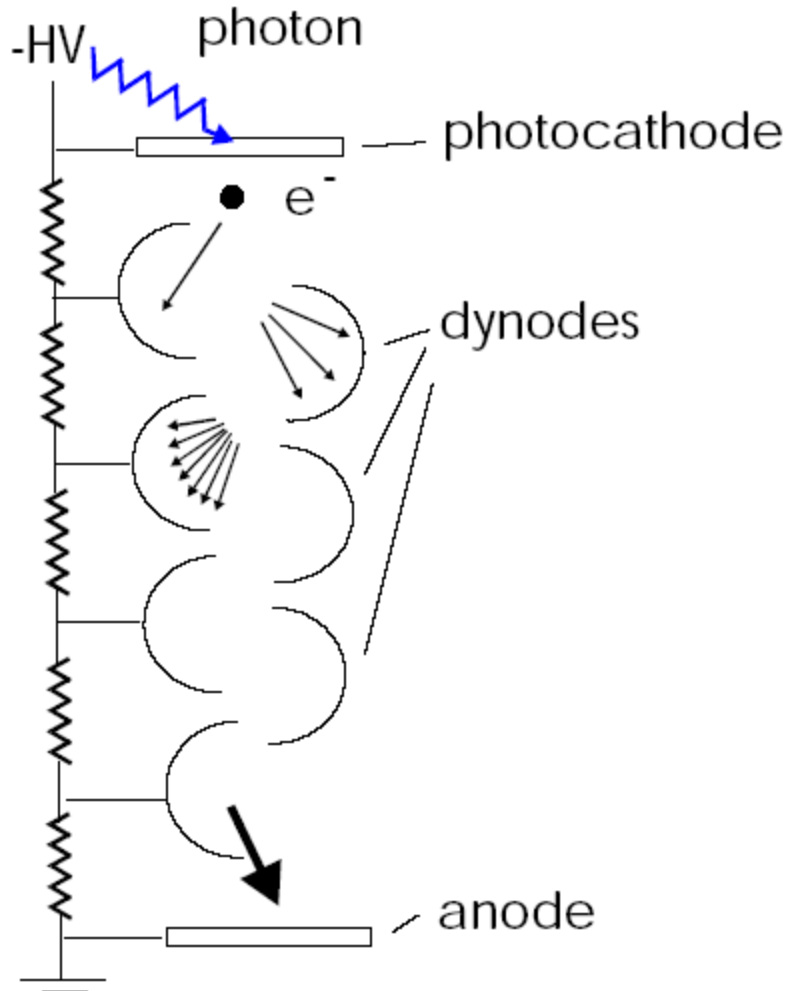
1. Photon shot noise
2. Instrument dark noise
3. Johnson noise
4. Detector characteristics
5. Photomultiplier tube

A typical biomedical optics experiment



Photomultiplier tube (PMT)

The PMT are characterized by two important parameters



Cathode sensitivity, S (A/W): 0.06 A/W

Gain, α : 10^7 to 10^8

We can relate current measured at the anode to the number of incident photons, n , arriving within a time interval Δt

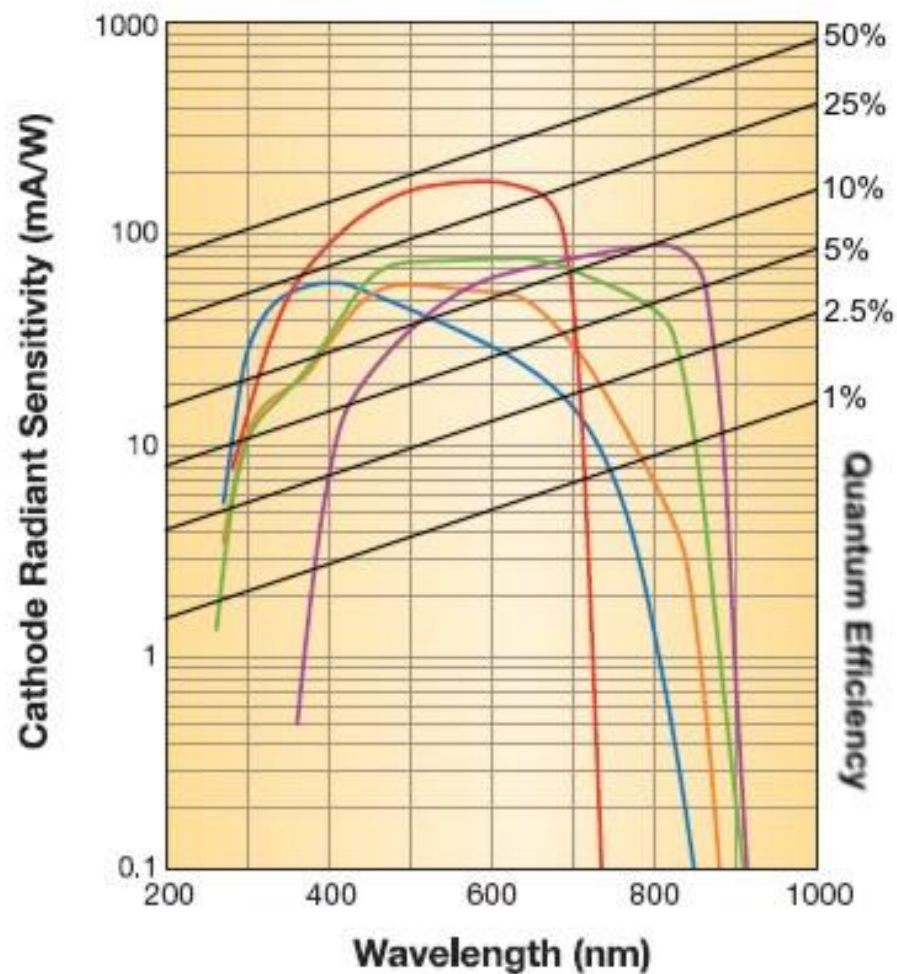
$$I = S \cdot \alpha \cdot E_{\gamma} \cdot n / \Delta t$$

E_{γ} is photon energy

For green (500 nm wavelength) photons:

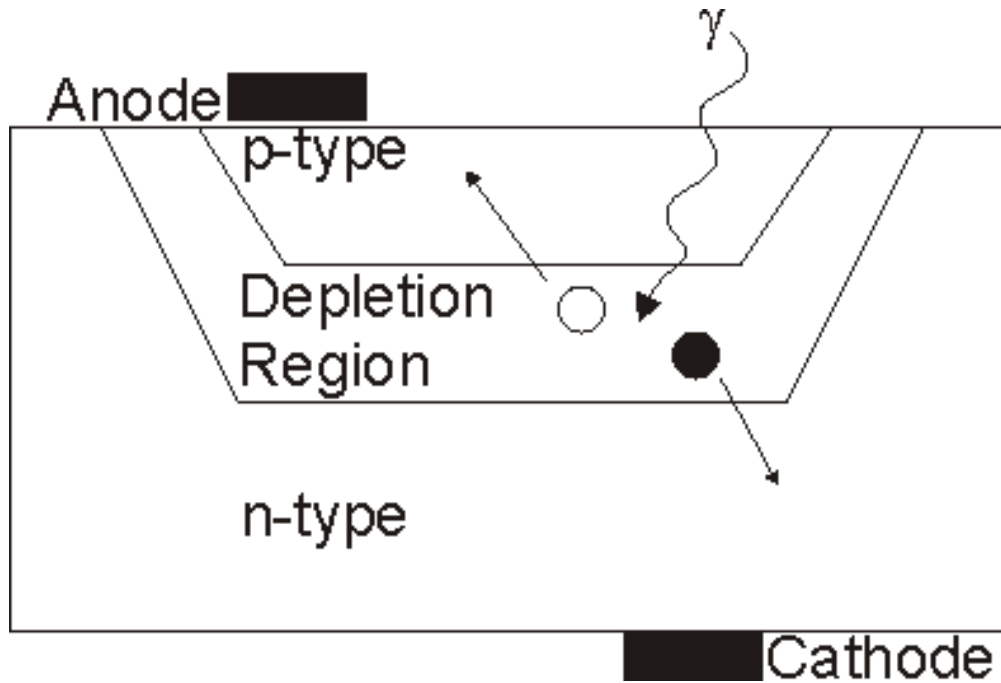
$$E_{\gamma} = \frac{hc}{\lambda} = \frac{6.6 \times 10^{-34} \text{ Js} \cdot 3 \times 10^8 \text{ m/s}}{5 \times 10^{-7} \text{ m}} = 4 \times 10^{-19} \text{ J}$$

Sensitivity of PMT Cathode as a Function of Material



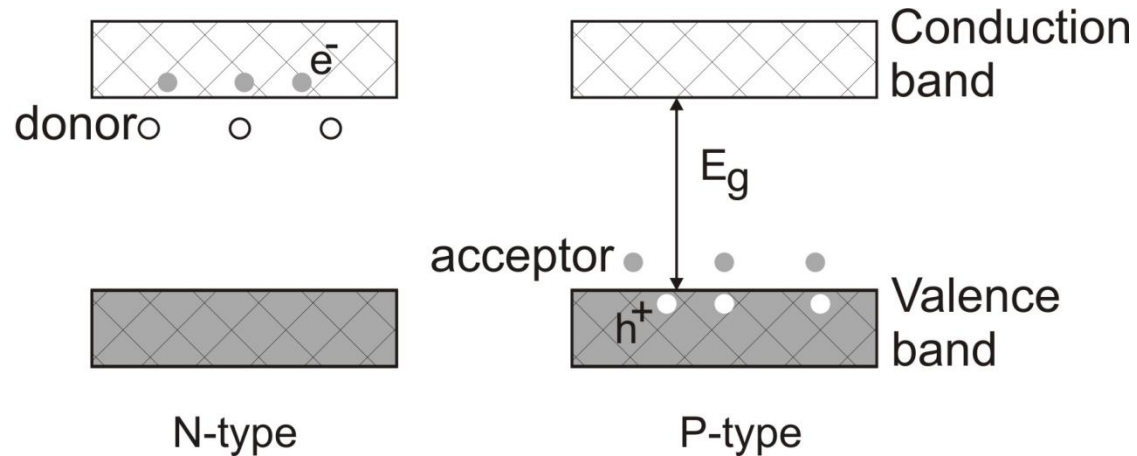
- Bialkali
- Gallium Arsenide Phosphide
- Extended Red Multialkali
- Multialkali
- Gallium Arsenide

Photodiodes

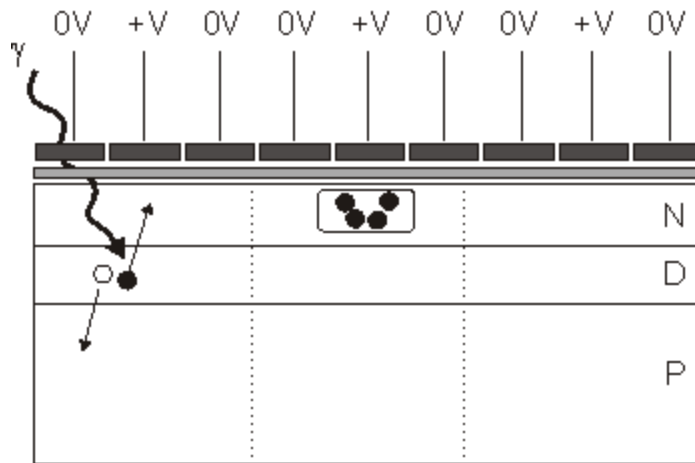


Biasing can increase
device temporal
Response speed

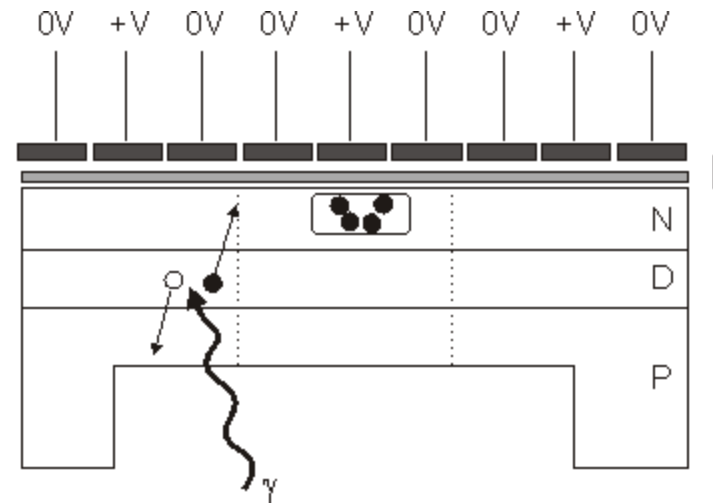
Recall:



Charge Coupled Device (CCD) Cameras

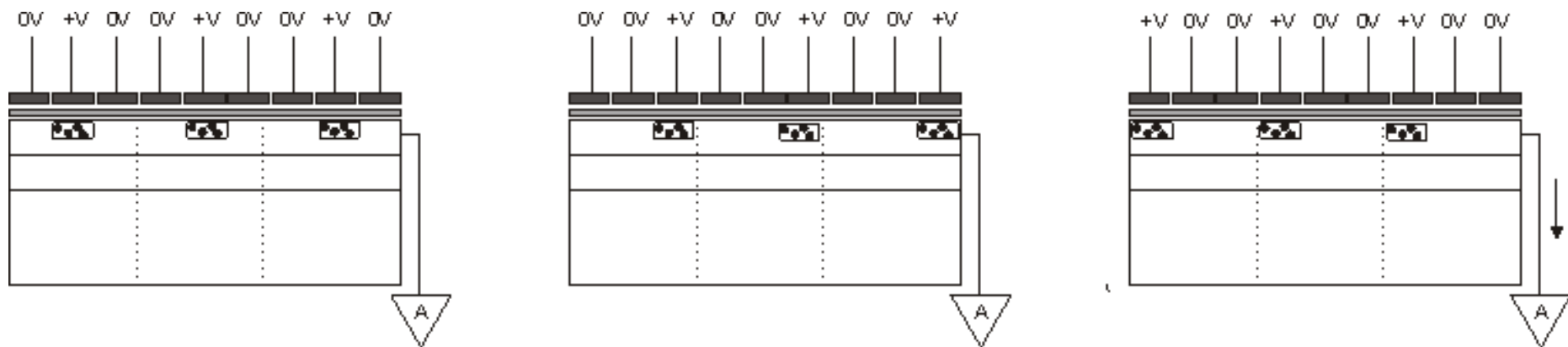


Front Illuminated



Back (thinned) Illuminated

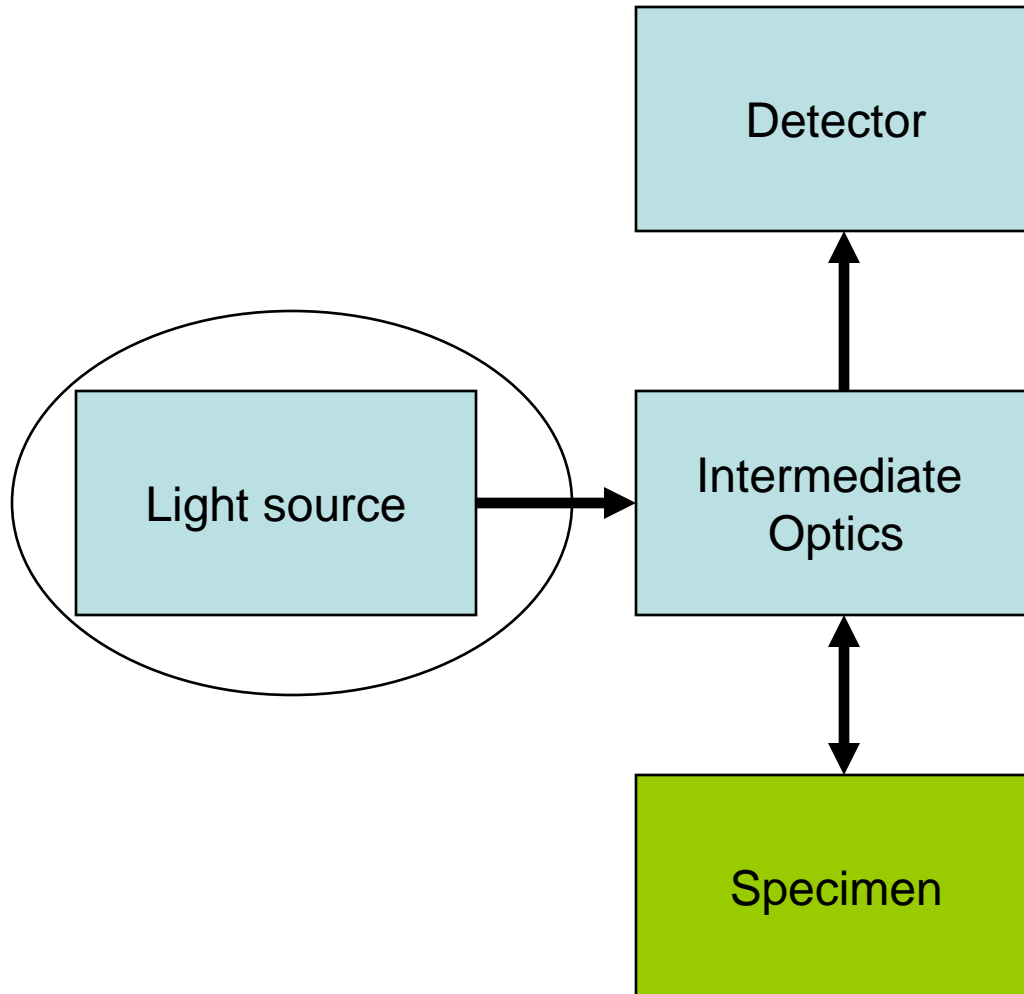
Readout Sequence Principle of CCD



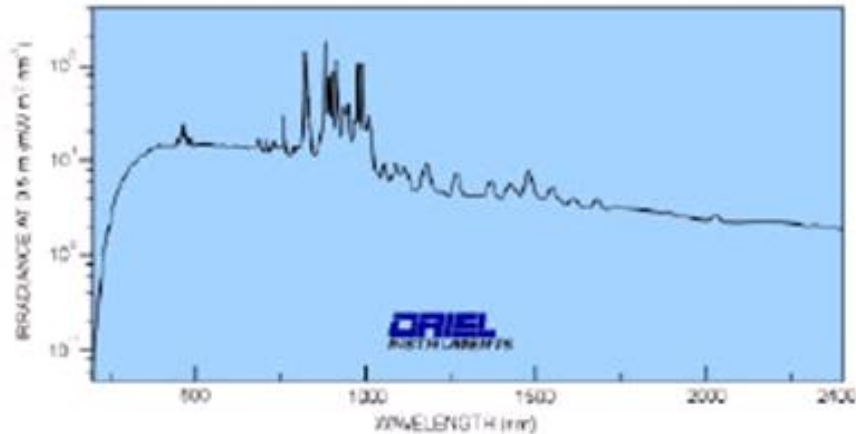
A Comparison of Detector Characteristics

	PMT	Photodiode	APD	CCD
QE	40%	80%	80%	80%
Spectral Range	UV-Green	Blue-NIR	Blue-NIR	Blue-NIR
Internal Gain	10^6 - 10^8	1	100-1000	1
Dark Noise	e ⁻ /sec	1000 e ⁻ /sec	e ⁻ /sec	e ⁻ /sec
Electronic (Read) Noise	NA	1000 e ⁻	NA	3-1000 e ⁻
Response Speed	+++	+++	+	-
Pixel Size	cm	mm	mm	μm

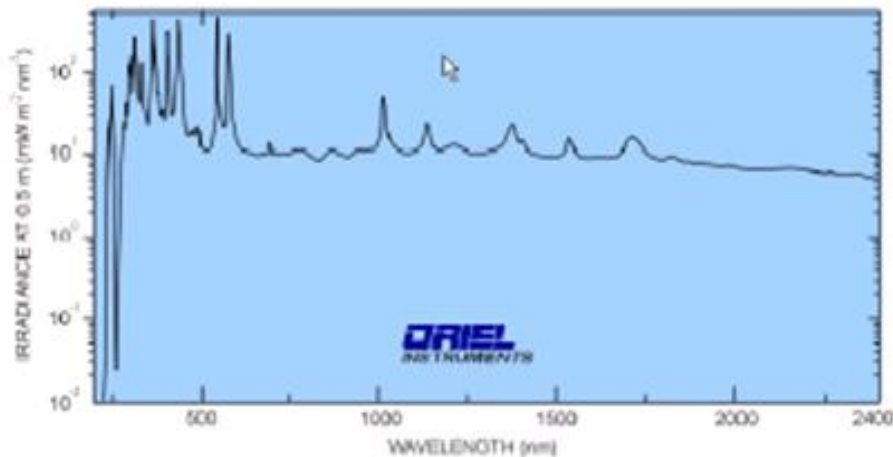
A typical biomedical optics experiment



Lamps – An Incoherent Light Source



Xenon arc lamp



Mercury arc lamp

Features of lamp source:

Broad spectral background – black body radiation

Sharp emission peaks – electronic transitions in gases

Uses of Lamp Source in Microscopy

Advantages: Low cost

Broadband or allow easy selection of spectral band

Ease of use

Disadvantages: Low spectral radiance (power within a given wavelength range)

High divergence (non-point source)

Lack of coherence

Xeon arc lamp: Smooth emission spectrum in the visible. The most common white light source in microscopy

Mercury arc lamp: Sharp emission lines in the near UV and blue green.
Broadband light source for fluorescence microscopy

Semiconductor Light Sources

Light emitting photodiodes: LEDs

They work by exciting electrons across a semiconductor bandgap (more of that later in the detector section) and their subsequent decay

Advantage of LED light source

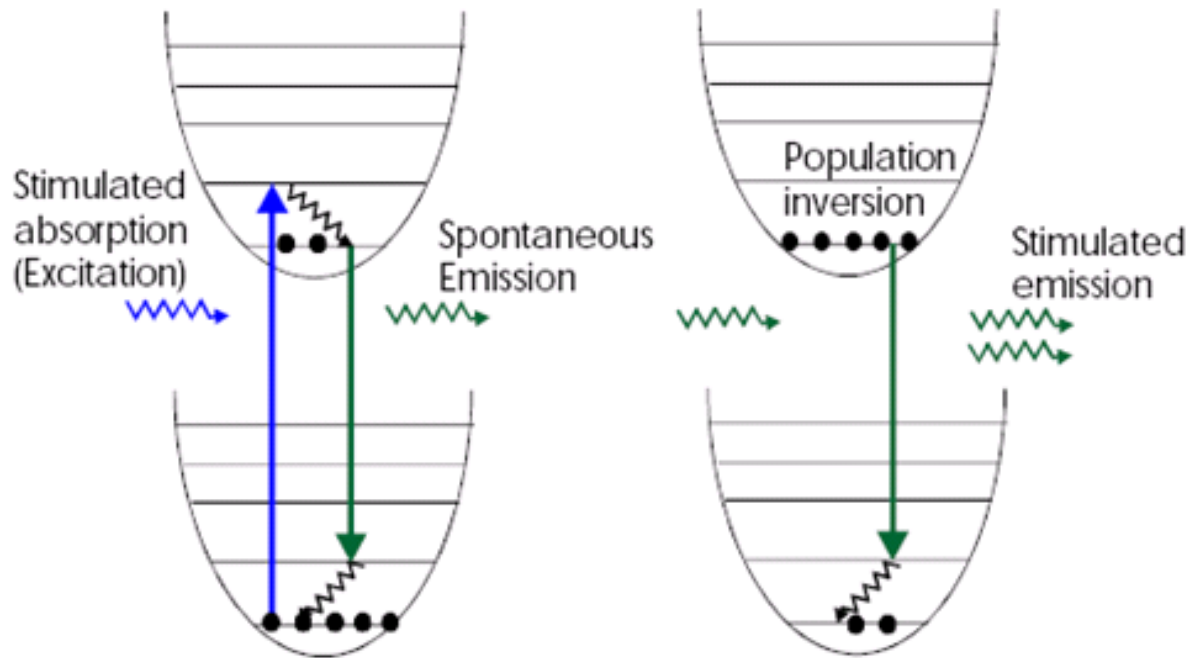
- * Relative narrow emission band
- * Low power consumption
- * High brightness
- * Long life
- * Can be modulated rapidly

Disadvantages of LED light source is similar to other lamps

Lasers – A Coherent Light Source

Laser = Light amplification of stimulated emission of radiation

Invented in 1950s by Charles Townes, Alexandr Prokhorov, & Nikolai Basov



Stimulation emission is the opposite of (stimulated) absorption

Stimulated emission is a “photon copier.”

The emitted photon has identical properties as the “stimulating” photon:
same color, direction, polarization: Indistinguishable

What does all these have to do with laser?

What is good about laser? What we want from a light source that a lamp is not?

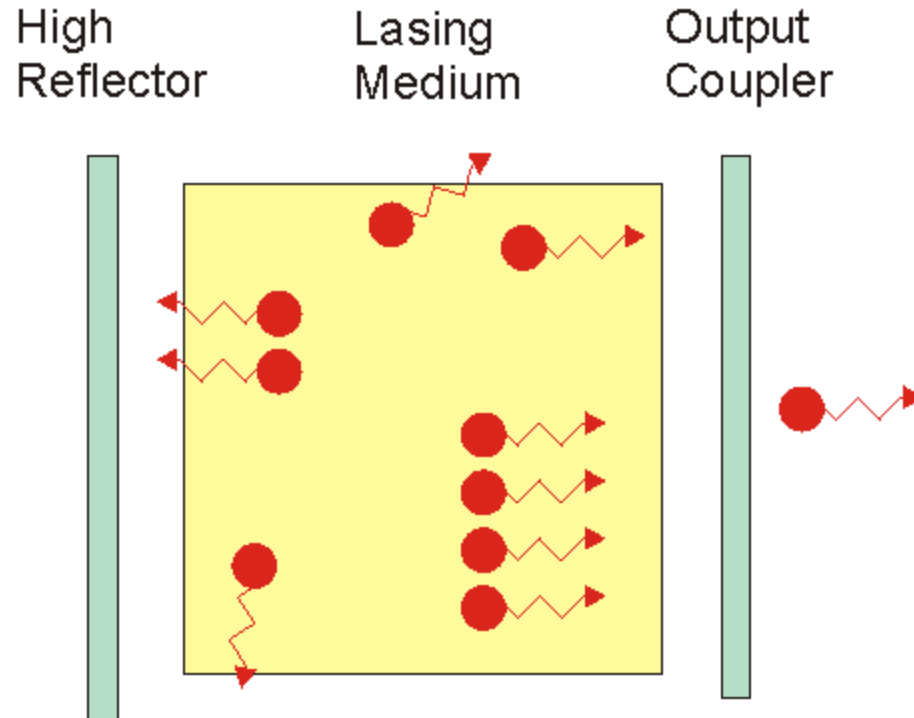
- (1) Monochromatic
- (2) High spectral radiance
- (3) Low divergence
- (4) Unique polarization
- (5) Long coherence length

How do we achieve this? If we can “copy” a photon many times. Then we have IT ... laser, Nobel prize,

We need two things: (1) amplification, (2) population inversion

Basic Idea of A Laser

Put a lasing medium in “population inversion” between two mirrors. An avalanche, amplification, process occurs as a spontaneous emitted photon bounce back and forth between the two mirrors to “copy” more of itself.



Uni-directionality comes from the fact that only photons going between the two mirrors are amplified.

Population inversion is needed so that the probability of stimulated emission is much greater than absorption to sustained the avalanche process

A Better Understanding of How Light Interaction with Molecules Is Needed to Know How to Create Population Inversion

Einstein studied these three processes: stimulated absorption,
Stimulated emission, and spontaneous emission

Let N_i, N_j be the population of molecules in the ground and excited states

Let I be the energy density of light

$$\frac{dN_j}{dt} = -B_{ji}N_jI - A_{ji}N_j + B_{ij}N_iI$$

At steady state, the ground and excited states population is constant:

$$B_{ij}N_iI = B_{ji}N_jI + A_{ji}N_j \quad \frac{N_j}{N_i} = \frac{B_{ij}I}{B_{ji}I + A_{ji}}$$

The relative populations of the states not only can be determined by kinetic consideration but also by thermodynamics

We also know from statistical mechanics that the populations of two states in thermal equilibrium is described by Boltzmann statistics

$$N_{i,j} = N_0 e^{-\frac{E_{i,j}}{kT}}$$

where E is the energy of states i and j , k is the Boltzmann's constant and T is the absolute temperature

$$\frac{N_j}{N_i} = e^{-\frac{(E_j - E_i)}{kT}} = e^{-\frac{\Delta E}{kT}}$$

Einstein B Coefficients

Combining kinetics and thermodynamics:

$$I = \frac{\frac{A_{ji}}{B_{ji}}}{\frac{B_{ij}}{B_{ji}} e^{\frac{\Delta E}{kT}} - 1}$$

What happens when temperature approach infinity?

We expect light density also grows to infinity
(driving all the molecules instantly to the excited state).

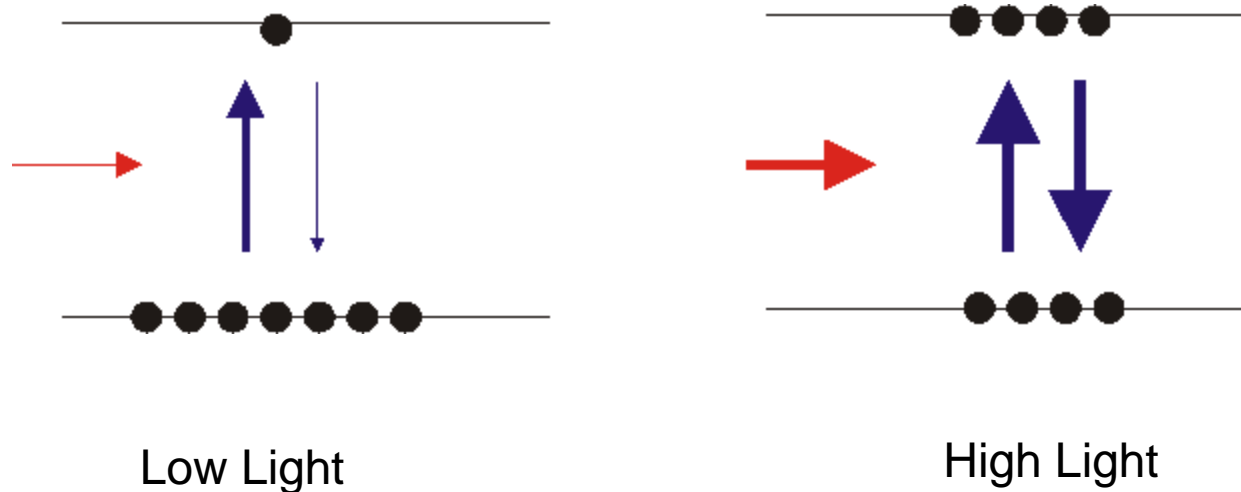
$$I \rightarrow \infty \quad \text{as} \quad T \rightarrow \infty \quad \text{requires} \quad B_{ij} = B_{ji} = B$$

“Einstein B coefficient”

The rate constants of stimulated absorption and emission are equal

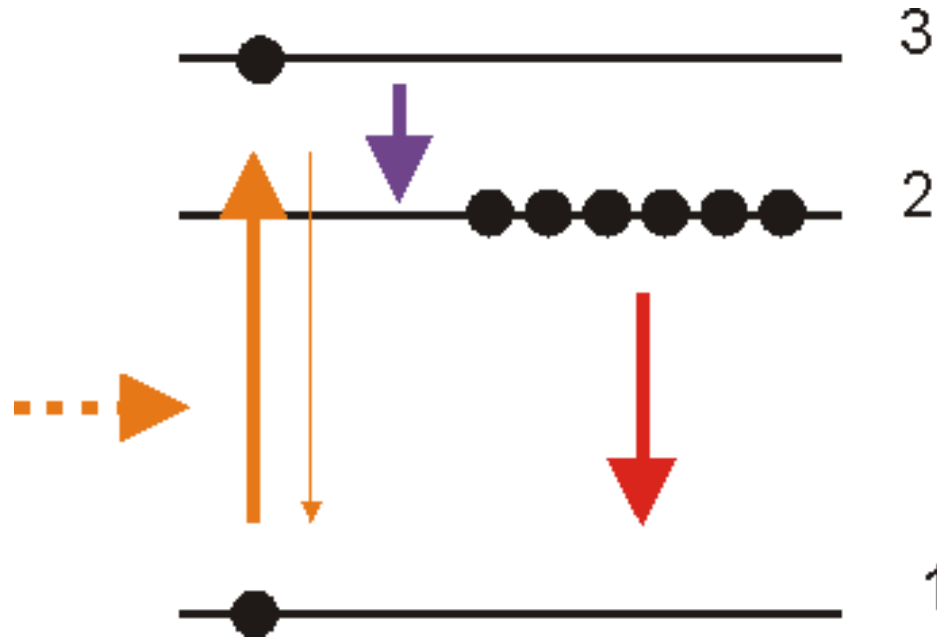
$$I = \frac{\frac{A}{B}}{e^{\frac{\Delta E}{kT}} - 1}$$

Population inversion is not possible in a 2-state system



As excited state becomes well populated, the excitation and de-excitation probability becomes equal because the Einstein coefficients for up and down are equal

Population inversion is possible in a 3-state system



Population inversion can be created if:

- (1) Spontaneous decay rate from state 3 to state 2 is the fastest
- (2) Stimulated excitation rate from state 1 to state 3 is faster or comparable to the decay rate from state 2 to state 1
- (3) Population inversion is created between state 1 and 2
- (4) Increasing “pump” power (orange) do not cause stimulated emission from state 2